Comparison of the accuracy of various transformations from multi-band images to reflectance spectra

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Technical Report

Comparison of the accuracy of various transformations from multi-band images to reflectance spectra

As part of end-to-end color reproduction from scene to reproduction using spectral imaging

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Abstract

This report provides a comparative study of the spectral and colorimetric accuracy of various transformations from multi-band digital signals to spectral reflectance. The multi-band channels were obtained by multi-channel visible-spectral imaging (MVSI) using a monochrome CCD and two different filtering systems. In the first system we used a liquid-crystal tunable filter (LCTF) capturing 31 narrow-band channels. We also used a filter wheel with a set of 6 glass filters imaging with and without an extra Wratten absorption filter giving a total of 12 channels. Four different mathematical methods were tested to derive reflectance spectra from digital signals: pseudo-inverse, eigenvector analysis, modified-discrete sine transformation (MDST) and non-negative least squares (NNLS). We also considered two different approaches to sampling the digital signals; in one approach we averaged the digital counts.

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I. INTRODUCTION

The ultimate goal of the research being conducted at the Spectral Color Imaging Laboratory (part of Munsell Color Science Laboratory, Chester F. Carlson Center for Imaging Science, Rochester Institute of Technology) is the design and evaluation of an end-to-end multi-channel visible-spectral imaging (MVSI) system to capture and reproduce works of art in a museum environment. This effort will facilitate the creation of highly accurate image archives since we are recording the most fundamental description of the imaging object, its reflection properties. This approach eliminates the necessity of visual editing, providing opportunities for color-accurate publication via multi-ink printing and generates powerful tools for conservation science. It is no secret that MVSI, also known as spectral imaging (for simplicity), has tremendous advantages over conventional trichromatic imaging. Our group have been researching various aspects of spectral imaging for a decade, spanning a wide range of aspects such as measurement, image acquisition, image synthesis, printing, and image processing.
In terms of image capture, we've compared various methods of acquisition, particularly a wide-band method based on a filtered trichromatic camera system and also a set of glass filters optimized to give simultaneously good colorimetric and spectral estimation accuracy. Although wide-band image acquisition are not as spectrally selective as the narrow-band approach, these approaches allow us to reduce the number of channels providing economy of storage space. Alternatively, we can use a series of narrow-band filters in order to get a better sampling of the spectra during the spectral imaging by the use of interference filters or liquid crystal tunable filters (LCTF). Interference filters have disadvantages such as angle of incidence dependence. We solved to adopt the use of LCTF for our narrow-band capture, although it presents a low transmittance characteristic, because we believed that having a filter system without mechanically moving parts will benefit the registration of the images compared to a system that has a mechanical filter wheel. Many other research groups also have been using LCTF imaging systems. We have already performed some preliminary experiments using LCTF and based on these past experiences we are now conducting a more detailed analysis of its performance for spectral image capture and spectral estimation. We are also extending our previous comparison study between wide-band and narrow-band acquisition systems presenting more detailed analyses.

II. EXPERIMENTAL

All the spectral estimations described in this report are based on a set of targets with measured spectral reflectance information. The targets are imaged using a multi-band camera and a transformation is built to get spectral reflectance from camera digital signals using a characterization target. Then, each transformation is applied to the digital signals of verification targets in order to derive the corresponding spectral reflectances. The estimated spectral data then are compared with the original measurements.

II.1. Hardware setup of the image capturing system

The image capturing system is shown in the diagram of Figure 1. It consisted of a Roper Scientific Photometrics Quantix monochrome digital camera with a filtering system (either narrow-band or wide-band). The camera is mounted on a Firenze minisalon stand. The digital camera is pointed through a cardboard baffle to a set of targets fixed with magnets and tape to an iron board secured to an adjustable easel. The baffle is used to reduce the flare from the illumination. Alternatively a bellow also can be used instead of the cardboard baffle. The targets are illuminated by two Elichron Scanlite Digital 1000 studio illumination lamps from a distance of approximately 150 cm. The distance between the extremity of the lens in the imaging system and the target is...
approximately 220 cm. The experimental MVSI camera is the “white box” in the center. A Nikon Professional SLR D1 digital camera with 2.75-megapixel CCD with 2,012 by 1,324 effective pixels is also used as a benchmark system and it is also mounted on the mini-salon stand. Both Quantix and Nikon camera systems are controlled from the same computer.

Here we present a more detailed description of our image acquisition system:

**II.1.A) Multi-band digital camera**

For the multi-band digital camera we selected the Roper Scientific, Inc. Photometrics Quantix 6303E camera that consists of a cooled, high-performance CCD camera system that uses a Kodak blue enhanced KAF6303E CCD. Quantix delivers true 12-bit images at a high-speed readout rate of 5 million pixels per second. Image integrity is protected by ultra-low-noise electronics that uses Peltier elements that keeps temperature to be approximately –28 C and consequently the noise is relatively low even for long exposures. A Unaxis/Balzers broadband near-infrared radiation reduction (cut-off) filter (UBO 110-RE) is always used with this imaging system. The Quantix 6303E has a pixel size of 9µm by 9µm with sensor size of 3,072 by 2,048 pixels.

Figure 2 shows a picture of the Quantix camera. The spectral sensitivity of this camera was measured using a monochromatic light and a spectroradiometer. Figure 3 shows the relative spectral sensitivity of the Quantix camera with the near-infrared cut-off filter.
Figure 1. Diagram of the image acquisition system.

Figure 2. Roper Scientific’s Photometrics Quantix Camera.
II.1.B) Filters

II.1.B.a. Narrow-band imaging with Liquid Crystal Tunable Filter (LCTF)

The cooled camera system is used in conjunction with the LCTF to capture narrow-band images. This approach presents many advantages such as automated capture by synchronizing the filter tuning with the camera shutter control and minimization of misregistration artifacts since the LCTF is electronically controlled providing rapid, vibrationless selection of any wavelength in the visible range, although some focusing problems could happen for different wavelength adjustments.

In our experiments we used a Cambridge Research & Instrumentation, Inc (CRI) Varispec Tunable Imaging Filter as our LCTF. The LCTF filter has a 35 mm aperture and it comes with the option for a high-contrast narrow-band and a medium-contrast broadband bandwidth. We are using the broad-band mode to get more throughput. Although it is called “broad-band” mode it is actually much narrower than an actual broad-band filter, e.g. an absorption Wratten filter. The LCTF was measured using the configuration shown in Figure 4. For the light source we used a xenon lamp with a power source manufactured by Ernst Leitz GMBH Wetzlen. This light source is more appropriate for the transmittance measurement than the tungsten lamp since it has more radiant power in the short wavelength region. We projected the xenon light on a halon surrounded by a black
cardboard as a light baffle in a dark environment. We used a PhotoResearch PR-650 spectroradiometer to measure the spectral power distribution of the light reflected from the halon through the LCTF as shown in Figure 5. The measured spectral power distribution was subsequently divided by the spectral power distribution of the xenon lamp reflected on the halon in order to calculate the LCTF spectral transmittance. The spectral transmittance of the LCTF is shown in Figure 6, sampled in intervals of 10 nm from 400 to 700 nm. From our measured data it is possible to see that the spectral transmittances decreases from the long to short wavelength and it has a maximum throughput of approximately 30% when it is tuned at 700 nm but its transmittance is around 4.5% for 400 nm. This implies very long exposure times for the short wavelength region of the spectrum. These peak values are much smaller than the nominal values given by CRI. However, it is not possible to compare the values since they used polarized light in the measurements, something that we did not do since \textit{a priori} we are not planning to use such kind of illumination in our imaging. The bandwidth also decreases progressively from the long wavelength to the short wavelength having a range from approximately 60 nm to 20 nm at a half peak. Moreover, Figure 7 shows the spectral transmittances corresponding to 400 nm, and we can observe that there is a serious problem of leaking in both short and long wavelengths. We also could observe this phenomenon when the filter was tuned to other short wavelengths. These leaks are a result of how LCTFs are built using polarizing filters. From Figure 8 we also can see that the spectral transmittance for the wavelength at 400 nm and 410 nm are contained in the spectral transmittance for the wavelength at 420nm. Please, note that Figures 6, 7 and 8 have different scales in the ordinate. We could avoid performing any imaging with the 400nm and 410nm adjustments since human subjects are not very sensitive at those wavelengths but it has the disadvantage of not being to distinguish various white pigments such as lead white and titanium white. Therefore, we solved to include these problematic wavelengths since we believe we could find a transformation from digital signals to reflectance that considers these leaks in other wavelength.
Figure 4. Diagram of the LCTF transmittance measurement.

Figure 5. Xenon light source, spectroradiometer and the LCTF being measured.
Figure 6. Spectral transmittance of the LCTF sampled in intervals of 10 nm from 400 to 700 nm. Note that the y-axis is scaled from 0 to 0.35.
Figure 7. Spectral transmittance of the LCTF centered at 400 nm. Note that the y-axis is scaled differently compared to the previous figure. Now it is scaled from 0 to 0.005.
Figure 8. Spectral transmittance of the LCTF centered at 400, 410 and 420 nm. Note that the y-axis is scaled differently compared to the previous figures. Now it is scaled from 0 to 0.06.

A Rodenstock 105 mm 1:5.6 enlarger lens with fstop half way between 5.6 and 8 was used with a modular focus ring to be connected to the LCTF and the LCTF in conjunction with the near-infrared cut-off filter is attached to the camera using a Nikon mount. Figure 10 shows a picture of the Quantix camera with the LCTF and lens attached to it.

Figure 9. Picture of the Quantix camera with the LCTF and the enlarger lens.

II.1.B.b. Wide-band imaging with glass filters
A set of six glass filters was designed to give the best colorimetric and spectral performance for our imaging system. The six filters are used in a filter wheel with 6 holes. Although we could perform a completely theoretical simulation to design the filter set we opted for using transmittance factors of actual glass filters manufactured by Schott. The Schott glass filter set consists of 14 band-pass filters, 7 IR cut-off filters and 18 long-pass filters. It is possible to get filters in 1mm, 2mm and 3 mm thickness. The spectral transmittances of the 40 filters are shown in Figures 10, 11 and 12 for respectively band-pass type, IR cut-off type and long-pass type filters. Since no individual filter of the possible 120 types can achieve a desired spectral transmittance characteristic, it is necessary to combine filters to increase the number of possible spectral shapes. Since the filter wheel hole has a depth of 4 mm, we have to constrain the total thickness to be equal or less than 4 mm. In order to simplify the problem we are only considering combination of two filters although it is theoretically possible to have three or four filters.

Figure 13 contains a diagram that summarizes how the filters were selected. Three filters corresponding to red, green and blue were selected colorimetrically, i. e., the cost functions to be minimized were only based on colorimetry. The details of this filter
design are beyond the scope of this report. The remaining three filters were pre-selected since all possible combinations will be prohibitive and they would not necessarily give the desired filter shapes. For example, we would like to avoid having filters that overlap with a lot of redundancy with other filters of the selected set. Therefore, some physical constraints were used in the pre-selection part. We forced one filter combination to have a system (considering camera spectral sensitivity and IR cut-off filter) response peak between 470 and 510 nm with maximum bandwidth of 80 nm, the second filter combination with a system response peak between 560 and 580 nm with maximum bandwidth of 60 nm and the last filter combination with a system response peak between 640 and 750 nm with a maximum bandwidth of 80 nm.

Figure 10. Spectral transmittance of band-pass type Schott filters.
Figure 11. Spectral transmittance of IR cut-off type Schott filters.

Figure 12. Spectral transmittance of long-pass type Schott filters.
The pre-selected filter combinations are combined with the previously determined RGB filter combinations and they are used in conjunction with camera response, illuminant used in the experiment and a set of spectral reflectances in a camera simulator that gives digital signals. The reflectance database consisted of 120 DuPont data, 64 Munsell patches and 170 object database, all downloaded from the University of North Carolina. Eigenvector analysis is performed for the spectral reflectance data to generate eigenvectors that are used in conjunction to the simulated digital signals to estimate spectral reflectances. The estimated spectral reflectances are compared with the original ones using various cost functions (color difference equations, RMS spectral error factor, weighted RMS spectral error factors, metamerism indices) and the filter combination that gives the overall best result was selected.

The pairs of designed filters were glued and they were cut to fit the holes of a mechanical filter wheel controlled by the same computer that controls the Quantix digital camera and, therefore, the imaging can be performed automatically. In order to adjust the imaging system with wide-band filter to fit the same angle of view from the same distance compared to the narrow-band imaging, a Nikor 105 mm lens was attached in front of the filter wheel. Although the Nikor 105 mm lens was not considered in the filter design we assume that its contribution is negligible to alter its results. The open filter wheel with the designed filters is shown in Figure 16.
Figure 13. Diagram of filter selection process.

The selected filters are shown in Figure 14 and the filters combined with camera system are shown in Figure 15.

Figure 14. Spectral transmittance of six selected filters.
**Figure 15.** Spectral response of the designed filters combined with camera spectral response with IR cut-off filter.

**Figure 16.** Open filter wheel with 6 designed glass filters.

II.1.B.c Wide-band RGB imaging with and without extra absorption filter

Our previous experiments showed that it is possible to use multiple RGB signals combining original RGB signals with filtered RGB (by actually filtering the RGB signals or by using a different illumination).\(^3^3\) We also tested this technique with our imaging system using the Quantix camera with the filter wheel only in the positions of the colorimetrically designed RGB filters mentioned in the previous section combined with a Wratten filter Number 38 (light blue filter) shown in Figure 17. Although this filter was selected based on a near-colorimetric IBM digital camera, we assume that it is a good selection for our system since our filters also have a near-colorimetric performance and uses similar illumination as the IBM digital camera system.
II.1.C) **Illuminant**

**Elichron Scanlite Digital 1000 Lamp**

The relative spectral power distribution of the lamp reflected on a piece of standard white halon is shown in Figure 18. This lamp has a spectral power distribution very similar to the CIE standard illuminant A.

![Figure 18. Relative spectral power distribution of the Scanlite lamp.](image)

II.1.D) **Targets**

The targets we used are shown in Figures 19a to 19f. The images of Figures 19a to 19f were on purpose not white-balanced to show the targets under the imaging illumination. For the targets we used objects containing uniform patches for characterization and verification, pictorial image and three-dimensional parts for image quality assessment:

1. Target 1 a) GretagMacbeth ColorChecker DC with 239 patches with sufficient color variability used as a universal color target in order to generate the transformation functioning as a training set.
   
   b) Gamblin paint target with 63 square targets containing common pigments.

2. Target 2 a) Kodak Gray Scale Q60 CAT 1527662 that consists of a gray scale used to check the photometric linearity of the system.
b) GretagMacbeth ColorChecker color rendition chart—consists of 24 patches, 6 grays and 18 colors; it was included in our imaging since it is widely used in the imaging community for comparison purposes.

c) Water Color paint—as a pictorial image.

3. Target 3—34 color card paint chips.
4. Target 4—Fake bird nest and chips of the ColorChecker.
5. Target 5—Fake fruits in a basket with chips of the ColorChecker.
6. Target 6—Baby toys.

All targets described above have a halon tablet for determining the proper exposure time without clipping the digital signal.

In addition, we also selected two color-aid papers: light gray (gray 7) and dark gray (gray 5) to perform correction for the non-uniformity of the illumination.
II.2. Spectral imaging and estimation

Camera setting

In the Quantix camera software, we selected Gain 2, readout speed of 5 MHz and offset setting of 2076 that gives a dark current digital signal of approximately 110. A
Matlab program was written in order to determine automatically the exposure time for each LCTF wavelength setting. The code was adjusting the exposure time in order to have mean digital signal of the central region of the halon at the Target 1 around 3,800. It gives some security margin below the maximum theoretical camera value of 4095 for our 12 bit imaging considering non-uniformity of illumination and illumination highlights.

For the narrow-band imaging we used the LCTF in wide-band low-contrast mode attached to the Quantix camera. The Balzers near infrared cut-off filter is attached to the LCTF. As a lens, we used Rodenstock 105 mm 1:5.6 enlarger with f-stop half stop between 11 and 16. The lens is attached to the LCTF with the help of a Rodestock modular-focus ring that provides precise focus adjustment.

For the wide-band imaging the LCTF is removed and the filter wheel with the set of six filters is attached to the camera body. A Nikkor 105 mm lens 1: 2.5 with fstop 11 is attached to the filter wheel lens adapter. A filter holder is attached to the Nikor lens to provide a place to hold the Balzers near infrared cut-off filter combined with a Kodak absorption filter 96 that is a neutral density filter 0.5 and an extra spot to slide mechanically the Wratten light-blue filter. The neutral density filter is necessary to give an exposure metering that is longer than 100 ms for every channel because the limitation in speed of the Quantix camera mechanical shutter. Figure 20 shows the Quantix camera with the filter wheel mounted on the stand with the Cokin filter adapter holding the set of filters. The light blue absorption filter is in the front of the filter holder.
Figure 20. Wide-band image with Glass filters in a filter wheel and light blue absorption filter.

Figure 21 shows a flowchart of the imaging and spectral estimation process that can be divided in five steps:

a) Exposure metering,
b) Imaging,
c) Generation of transformations from digital signals to reflectance,
d) Spectral estimation,
e) Evaluation of the spectral performance

Each step is described in detail below.
II.2.A. Exposure metering

Table I shows the exposure time used for each channel. The exposure time was determined so we have at least an exposure time of 100 ms for the shortest exposure since any exposure time less than 100 ms is uncertain for our imaging system. If we consider a readout of 3 seconds for each image, from Table I we can calculate that the whole imaging takes approximately 6.2 minutes. The total time decreases to 4 minutes if we do not consider the imaging corresponding to the LCTF centered at 400 nm and 410 nm. Figure 22 shows a plot of exposure time versus wavelength. The exposure time for the LCTF centered at 400 nm was lower than the exposure time required for 410 nm because the leaks shown in Figure 7.

Table II shows the exposure time used for each channel of the wide-band imaging.

Table I. Exposure time from 400 nm to 700 nm settings for the LCTF.

<table>
<thead>
<tr>
<th>LCTF wavelength (nm)</th>
<th>400</th>
<th>410</th>
<th>420</th>
<th>430</th>
<th>440</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure time (ms)</td>
<td>51424</td>
<td>76849</td>
<td>47603</td>
<td>30972</td>
<td>20622</td>
</tr>
<tr>
<td>LCTF wavelength (nm)</td>
<td>450</td>
<td>460</td>
<td>470</td>
<td>480</td>
<td>490</td>
</tr>
<tr>
<td>Exposure time (ms)</td>
<td>13793</td>
<td>9529</td>
<td>7076</td>
<td>4367</td>
<td>3447</td>
</tr>
<tr>
<td>LCTF wavelength (nm)</td>
<td>500</td>
<td>510</td>
<td>520</td>
<td>530</td>
<td>540</td>
</tr>
<tr>
<td>Exposure time (ms)</td>
<td>2741</td>
<td>2166</td>
<td>1477</td>
<td>1191</td>
<td>962</td>
</tr>
<tr>
<td>LCTF wavelength (nm)</td>
<td>550</td>
<td>560</td>
<td>570</td>
<td>580</td>
<td>590</td>
</tr>
<tr>
<td>Exposure time (ms)</td>
<td>797</td>
<td>673</td>
<td>577</td>
<td>505</td>
<td>382</td>
</tr>
<tr>
<td>LCTF wavelength (nm)</td>
<td>600</td>
<td>610</td>
<td>620</td>
<td>630</td>
<td>640</td>
</tr>
<tr>
<td>Exposure time (ms)</td>
<td>340</td>
<td>265</td>
<td>236</td>
<td>212</td>
<td>191</td>
</tr>
<tr>
<td>LCTF wavelength (nm)</td>
<td>650</td>
<td>660</td>
<td>670</td>
<td>680</td>
<td>690</td>
</tr>
<tr>
<td>Exposure time (ms)</td>
<td>173</td>
<td>158</td>
<td>146</td>
<td>131</td>
<td>129</td>
</tr>
<tr>
<td>LCTF wavelength (nm)</td>
<td>700</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exposure time (ms)</td>
<td>135</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table II. Exposure times for the wide-band imaging.

<table>
<thead>
<tr>
<th>Filter</th>
<th>Blue</th>
<th>B-G</th>
<th>Green</th>
<th>G-R</th>
<th>Red</th>
<th>NIR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure time without light blue filter (ms)</td>
<td>2378</td>
<td>812</td>
<td>900</td>
<td>663</td>
<td>686</td>
<td>118</td>
</tr>
<tr>
<td>LCTF wavelength with light blue filter (nm)</td>
<td>3500</td>
<td>1690</td>
<td>2050</td>
<td>2150</td>
<td>4500</td>
<td>1850</td>
</tr>
</tbody>
</table>

II.2.B) Imaging

The imaging process was divided in the following items:

a. Imaging targets
b. Imaging the uniform gray card
c. Imaging the dark image
d. Normalizing the digital signals.

All these images were necessary to compensate for illumination non-uniformity, dark current noise and at the same time providing the best dynamic range possible.

II.2.B.a. Imaging targets - two imaging sessions were performed to produce after processing, respectively a set of 31 narrow-band images with LCTF and a set of 12 wide-band images. In the case of wide-band images, a set of images were taken for each 6 filter in the wheel without an external absorption filter and with Kodak Wratten filter 38 (light blue) resulting in 12 channels. It results in two possible wide-band multi-
channel sets. The first one uses only the six channels taken without the absorption filter. The second one uses only the RGB signals taken with and without external absorption filter.

II.2.B.b. Imaging the uniform gray card – two color-aid papers: light gray (gray 7) and dark gray (gray 5) were imaged with each of the exposure times for wide-band imaging and for some wavelength settings for the narrow-band imaging. Figure 23 shows a gray uniform paper being imaged.

Figure 23. Gray color-aid paper imaging.

II.2.B.c. Imaging the dark current image – The dark current image was taken with the shutter closed with the same exposure used to image the target for each band.

II.2.B.d. Image normalization - The multi-band image was generated for each wavelength by subtracting the dark current noise and normalizing the digital signals to take in account the non-uniformity of the illumination. This process can eventually generate digital signals over the maximum of 4,095 for 12 bits due to highlights in the image. These digital values were clipped to equal 4,095.

Figure 24 shows a general view of our imaging in action.
II.2.C. Generation of transformations from digital signals to reflectance

The generation of the transformation from digital signals to reflectance is a very critical part of the spectral estimation process.

In order to provide an independent verification of our spectral estimation results, the transformation from digital signals to reflectance was generated for a training set consisting of digital signals and measured reflectances of the GretagMacbeth ColorChecker DC. In order to test the accuracy of the calculations the generated transformation was used to estimate the reflectance of the ColorChecker DC itself. For independent verification we considered verification targets consisted of the GretagMacbeth ColorChecker rendition chart, the Gamblin painting target and the color card painting chips. This verification provides information about the robustness of the transformation for independent targets. We are particularly interested in the performance for the Gamblin paint target since our main goal is spectral imaging and estimation of artwork paintings. In a preliminary experiment, the color card painting chips were also used as a training set but it was abandoned due to low spectral accuracy of the transformation it generated. This lack of accuracy was probably due of the poor sampling of color space when the color card paint chips were used.

There are many different ways to generate the inverse transformation from digital signals to reflectance. In this research we considered the number of samples used in the calculation of the inverse transformation and the mathematical method.

We considered two approaches. In the first approach we averaged the digital signals over the region of each uniform patch considered in the experiment and used these averaged digital signals to derive and test the transformations. This approach is very
simple to implement but reduced the whole universe of digital values captured by the
camera to a series of average single numbers neglecting the variability and uncertainty
aspects of the imaging. Alternatively it is possible to mask a cluster of pixels and build
transformation from all those corresponding digital signals to reflectance. This last
approach can potentially use millions of digital signals demanding increase of processing
power but we believe it potentially can derive more robust transformations by taking in
account the variability of the camera signals.

We also have to consider which mathematical technique is the best one to derive
the inverse transformation from digital signals to reflectance. Among the researchers who
have compared different spectral reconstruction transformations from camera digital
signals we have to mention Burns and Berns,69 who compared results of transformation
based on eigenvector analysis with interpolation methods such as cubic spline and
modified-discrete-sine-transformation abbreviated as MDST70 from digital signals using a
monochromatic camera and a set of seven interference filters. Working with simulated
camera signals and not actual digital signals, König71 performed a comparative study of
spectral estimation accuracy for different transformation techniques such as spline
interpolation, MDST, smoothing inverse72 and pseudo-inverse calculations varying the
bandwidth of the filter. Haneishi, et al. used Wiener filtering to estimate spectra from
camera signals.73

From our experience with inverse transformation generation, a mathematically
accurate pseudo-inverse transformation may not possess a physical meaning. As a result a
transformation in most cases fits very well mathematically the training set but it does not
have stability or robustness for a different verification targets due to its inherent lack of
physical meaning. For instance, in the narrow-band imaging, we believe that such a
transformation should have some non-zero non-diagonal terms but with weight
concentrated on the diagonal. In order to check this assumption we performed an a priori
experiment in which we used the Vrhel reflectance database74 with the measured spectral
response of the camera system using the system constituted by LCTF and near-IR cut-off
filter and also the spectral radiance of the illuminant to simulate digital camera signals.
Figure 27 shows the correlation between simulated radiance coming from the theoretical
Vrhel data and the digital signals generated by the camera model. Although this figure
shows correlation coefficients between radiance and digital signals we also expect that
the same trend will be observed for the correlation between reflectance and digital
signals. As expected, it is possible to observe from Figure 25 that there is a strong
correlation in the diagonal region since the LCTF were very spectrally selective for the
wavelength to which it was tuned. Therefore it is desirable to generate a transformation
that correlates somewhat to the physical properties visualized in Figure 25.
In our experiments we considered the following methods to calculate the spectral reflectances from digital signals:

II.2.C.a. Narrow-band imaging
For narrow-band images we considered the following methods to calculate the transformation matrix: pseudo-inverse transformation, eigenvector analysis with least squares, non-negative least squares, and MDST.

II.2.C.a.1 Pseudo-inverse transformation
A 31 by 31 transformation was derived by minimizing the least square error between measured and estimated reflectances from 31 channel images.

II.2.C.a.2. Eigenvector analysis with least squares
A two-step process using eigenvectors was used to generate a 31 by 31 transformation. The digital signals of 31 channels were used to predict the eigenvector coefficients and the coefficients were used in conjunction with the eigenvectors to estimate the reflectances. Therefore, the 31 by 31 transformation was a result of the multiplication of two sets of 31 by n and n by 31 transformations (where n is the number of eigenvectors) Since it is unknown a priori how many eigenvectors are necessary to have sufficient accuracy in the estimation, an experiment should be conducted to evaluate the estimation accuracy as a function of the number of eigenvectors.

II.2.C.a.3 Modified-discrete sine transformation (MDST)

In this method we used the assumption that any arbitrary spectra can be decomposed into a linear and a non-linear component. The non-linear component is approximated using the discrete sine transformation (DST). The linear component is used to force the non-linear component to be non-zero in the extremes of the visible range by an offset and slope adjustment. In our experiment, we vary the number of the sine curve nodes from 3 (when we have a sine curve with period equal to 300 nm spanning the entire visible region of the spectra from 400 nm to 700 nm) to 31 nodes, increasing progressively the number of the sine curve lobes. The high-order components corresponding to sine curves with many nodes can account for the reconstruction of spectra with sudden variation. Since it is unknown a priori which order for the DST should be used to produce sufficient accuracy in the spectral estimation, an experiment should be conducted to evaluate the estimation accuracy as a function of the DST order from 3 to 31 nodes.

II.2.C.a.4. Non-negative least squares (NNLS)

Non-negative least square optimization was used to derive a transformation matrix with all positive values. We believe it is a valid mathematical method to generate a transformation that can correlate well with physical properties of the imaging. As an additional feature, we are also changing the adjacent region around the diagonal of the transformation matrix where we allow non-zero values. Since it is unknown a priori how many non-zero adjacent lines around the diagonal result in sufficient spectral accuracy of the estimation, we should carry out an experiment to evaluate the spectral estimation as a function of the number of adjacent lines to the diagonal from zero (only diagonal terms) to 30 (the entire 31 by 31 matrix with non-zero values).

II.2.C.b. Wide-band imaging

For the wide-band channels we tested the pseudo inverse transformation and eigenvector analysis followed by a least-square transformation to produce a relation between digital signals and reflectance.
II.2.C.b.1 Pseudo-inverse transformation
A 6 by 31 transformation was derived by minimizing the least square error between measured and estimated reflectances from 6 channel images.

II.2.C.b.2 Eigenvector analysis with least squares
A two-step 6 by 31 transformation was derived. The first transformation was a least-square fit between 6 channel digital signals and 6 eigenvector coefficients. The 6 coefficients were then combined with 6 eigenvectors to derive the 31 dimensional reflectance.

II.2.D. Spectral estimation
Using the transformation generated for the ColorChecker DC, the reflectances of ColorChecker DC itself and the verification targets consisting of ColorChecker, Gamblin paint target and the paint chips were estimated from their corresponding digital signals.

II.2.E. Evaluation of the spectral performance
Since there is no single metric that can express the accuracy of spectral estimation we used a set of metrics:
1. Color difference equations such as $\Delta E^*_{ab}$ and $\Delta E^*_{00}$.
2. Spectral curve difference metrics such as root mean square error (RMS) as well as weighted RMS, using the inverse of the reflectance and the diagonal of the matrix $[R]$ as weights.
3. Metamerism index
Details of these metrics are presented in the Appendix.

II.3. Summary of the experiments
In our experiments we considered two different approaches for sampling: averaging the patches and using a cluster of pixels for each patch; two different types of imaging: narrow-band and wide-band; and four types of mathematical methods to generate transformations from digital signals to reflectances, summarized in Table III. For the average based approach we performed some a priori experiments to determine the best transformation for eigenvector, MDST and NNLS transformation according to the variation in its parameters. The pixel based approach that considers a cluster of pixels per patch (without averaging) is computationally very intensive and only some of the methods were implemented.

Table III. Experiments performed
### Method of generating transformation – Narrow-band

<table>
<thead>
<tr>
<th>Determination of the optimal “m” number of eigenvectors</th>
<th>Averaged digital signals per patch (average based)</th>
<th>Non-averaged digital signals per patch (pixel based)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
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<td>X</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Determination of the optimal “p” order of the MDST transformation</th>
<th>X</th>
<th>X</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Determination of the optimal “q” number of adjacent lines for NNLS</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudo-inverse</td>
<td>X</td>
</tr>
<tr>
<td>Eigenvectors and least-squares using “m” eigenvectors</td>
<td>X</td>
</tr>
<tr>
<td>MDST method using order “p” for the DST</td>
<td>X</td>
</tr>
<tr>
<td>NNLS with “q” adjacent lines to the diagonal</td>
<td>X</td>
</tr>
</tbody>
</table>

### Method of generating transformation – Wide-band

<table>
<thead>
<tr>
<th>Averaged digital signals per patch (average based)</th>
<th>Non-averaged digital signals per patch (pixel based)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pseudo-inverse</td>
<td>X</td>
</tr>
<tr>
<td>Six eigenvectors and least-squares</td>
<td>X</td>
</tr>
</tbody>
</table>

Figure 26 shows a schematic diagram of the generation of the transformation from digital signals to reflectance using the training target. The spatially and dark corrected images are masked to extract the coordinates and digital signals of areas corresponding to the uniform patches. It will result in \( k \) band images (\( k=31 \) for our narrow-band imaging and \( k=6 \) for our wide-band imaging), with \( r \) patches (\( r=240 \) for our training target that is the ColorChecker DC) giving \( s \) pixels per patch. In the average based approach, the pixel digital signals are averaged for each patch resulting in \( k \) bands with \( r \) digital signals and in the pixel based approach all the pixels inside the patch region are used in the calculations resulting in \( k \) bands with \( r*s \) digital signals. The designated mathematical methods for narrow-band and wide-band images are applied for both average based and pixel based approaches and a series of transformations are generated for the training target.

Figure 27 shows a schematic diagram of the spectral estimation and accuracy evaluation for the verification targets using the transformation from digital signals to reflectance generated by the training target.

Before using the transformation, the spatially and dark current corrected images with \( k \) bands are masked to extract the pixel corresponding to the \( t \) uniform patches (for instance, \( t=24 \) for the ColorChecker) with \( u \) pixels per patch. The derived transformations were then applied to the corresponding approach: either average based or pixel based. The estimated reflectance was compared to the measured reflectances.
The evaluation of the average based approach was straightforward. The estimated \( t \) reflectances were compared with the measured \( t \) reflectances using colorimetric and spectral quality metrics. For the pixel based approach, the measured reflectances of \( t \) uniform patches were replicated \( u \) times each to compare pixel by pixel to the estimated \( t \times u \) reflectances. Finally the results for the pixel-based and average-based approaches were compared.

III. RESULTS
The spectral imaging, estimation and evaluation experiments described in Figure 21 were performed using the approaches and methods described in the schematic diagrams of Figures 26 and 27. The training target used to derived the transformation from digital signals to reflectance spectra was always the GretagMacbeth ColorChecker DC. For the wide-band images, an additional process involving image registration was accomplished before extracting the digital signals from the images.

III.1. Average-based approach
Four different methods were employed for the narrow-band imaging and two different methods were employed for the wide-band imaging with 6 glass filters.

III.1.A. Narrow-band imaging using averaged digital signals
The transformation generated using the pseudo-inverse is represented in Figure 28. Figure 28 shows a tri-dimensional representation of the transformation matrix. In all the visualization figures shown in this report, the z-axis shows the numerical value of the matrix; the x-axis is the LCTF wavelength number, where 1 corresponds to a tuning to 400 nm, 2 corresponds to a tuning to 410 nm and so on until 31 corresponds to a tuning to 700 nm; and the y-axis is the wavelength number of reflectance where 1 corresponds to 400 nm, 2 corresponds to 410 nm and so on until 31 corresponds to 700 nm. From Figure 28, we can see that the transformation provided by pseudo-inverse lacks the desired physical property of strong correlation between digital counts and spectra shown in Figure 25.
Non-uniformity and dark current correcte multi-band image

Methods for Narrow-band images:
1) Pseudo-inverse
2) Eigenvector (number of eigenvectors are varied from 1 to 31)
3) MDST (order is varied from 3 to 31)
4) NNLS (number of adjacent lines are varied from 0 to 30)

Methods for Wide-band images:
1) Pseudo-inverse
2) Eigenvector (with 6 eigenvectors)

Figure 26. Schematic diagram of the generation of the transformation from digital signals to reflectance using the training target.
Figure 27. Schematic diagram of the generation of the transformation from digital signals to reflectance using the training target.
Figure 28. Visualization of the transformation matrix from averaged digital counts to reflectance using pseudo-inverse.

For the narrow-band imaging it is necessary to determine which transformation is the optimal one for eigenvector transformation, NNLS and MDST.


The transformation was derived for the GretagMacbeth ColorChecker DC varying the number of eigenvectors from 1 to 31 and spectra of the patches were reconstructed in order to select the minimum number of eigenvectors necessary for reasonable accuracy in the spectral estimation. The Table A.I.c in the Appendix shows the dependency of spectral estimation accuracy of ColorChecker DC reflectances from camera signals on the number of ColorChecker DC eigenvectors in terms of the average values of the various metrics. The Table A.I.b shows the dependency of spectral estimation accuracy of the ColorChecker DC reflectances from camera signals on the number of ColorChecker DC eigenvectors in terms of the worst performance of the metrics (minimum GFC and maximum values for the rest of the metrics). Table A.I.c in the Appendix shows the dependency of spectral estimation accuracy of ColorChecker DC reflectances from camera signals on the number of ColorChecker DC eigenvectors in terms of the standard deviation performance of the metrics. Figure 29 shows the average ΔE*00 and RMS error (%) plot between measured and estimated reflectance of ColorChecker DC varying the eigenvector numbers from 1 to 31. Figure 30 shows the
same information when the eigenvector numbers are varied from 1 to 8 in order to close up the region in which the colorimetric and spectral metric stabilizes.

Observing Tables A.I.a, A.I.b and A.I.c, as well as Figures 29 and 30, it is possible to see that increasing the number of eigenvectors from 1 to 31 improves the spectral estimation performance in terms of all considered metrics. However, the improvement stabilizes quickly and the benefit of increasing the number of eigenvectors is negligible beyond six eigenvectors. From Table A.I.a it is possible to see that all average metric values reach an asymptote without reaching a perfect match showing the theoretical limit probably due to noise. We also observed the same trend for accuracy varying the number of eigenvectors for the independent targets.

![Figure 29. Mean $\Delta E'_{00}$ and RMS error (%) between measured and estimated reflectance in function of the number of eigenvectors from 1 to 31, using averaged digital counts.](image)
Figure 30. Mean $\Delta E^{*} \_00$ and RMS error (%) between measured and estimated reflectance in function of the number of eigenvectors from 1 to 8 using averaged digital counts.

Selecting six eigenvectors as the optimal number of eigenvectors, we smooth the 31 by 31 transformation by decomposing it in two transformations: 31 by 6 transformation from the coefficients of eigenvectors to reflectances and 6 by 31 transformation from digital signals to coefficients of eigenvectors. Figure 31 shows a visualization of the transformation from digital signals to reflectance using six eigenvectors. From Figure 31 it is possible to see that the transformation presents oscillations between positive and negative values and it did not correlate well with Figure 25.
Figure 31. Visualization of the transformation matrix from averaged digital signals to reflectance using six eigenvectors.

III.1.A.b. Determination of the number of non-zero adjacent lines in the NNLS transformation using average digital signals necessary for accurate spectral estimation.

Table A.II.1 in the Appendix shows the dependency of spectral estimation accuracy of ColorChecker DC reflectances from camera signals on the number of non-zero adjacent lines in both sides the diagonal of the matrix, in terms of the average values of the metrics. Table A.II.2 in the Appendix shows the dependency of spectral estimation accuracy of ColorChecker DC reflectances from camera signals on the number of adjacent lines in both sides of the diagonal of the matrix, in terms of the worst performance of the metrics. Table A.II.3 in the Appendix shows the dependency of spectral estimation accuracy of ColorChecker DC reflectances from camera signals on the number of adjacent lines in both sides of the diagonal of the matrix, in terms of the standard deviation of the values of the metrics.

Figure 32 shows the average $\Delta E^{*\text{ab}}$ and RMS error (%) plot between measured and estimated reflectance of ColorChecker DC varying the number of non-zero adjacent lines in both sides of the diagonal from 0 to 30. Figure 33 shows the same information when the number of non-zero adjacent lines to the diagonal is varied from 1 to 5 in order to close up the region in which the colorimetric and spectral metric stabilizes.

Observing Tables A.II.1, A.II.2 and A.II.3 as well as Figures 32 and 33 it is possible to see that increasing the number of adjacent lines in both sides from 0 to 30
improves the spectral estimation performance in terms of all considered metrics. However, the improvement stabilizes very quickly and the benefit of increasing the number of non-zero adjacent lines to diagonal is negligible beyond three adjacent lines. From Table A.II.1 it is possible to see that all average metric values reach an asymptote without reaching a perfect match showing the theoretical limit probably due to noise. We also observed the same trend for accuracy varying the number of non-zero adjacent lines to the diagonal of NNLS for the independent targets.

Figure 34 shows a visualization of the transformation from digital signals to reflectance using NNLS transformation with three adjacent non-zero lines in both sides of the diagonal. In this transformation, for example when we use signals from the LCTF center in 560 nm, the coefficients of the matrix corresponding to the wavelength 530, 540, 550, 560, 570, 580 and 590 are non-zero and the rest of the coefficients are zero. This transformation showed strong correlation between digital signals and reflectance without having negative values.

Figure 32. Mean ΔE*₀₀ and RMS error (%) between measured and estimated reflectance in function of the number of non-zero adjacent lines to the diagonal from 0 to 30 using averaged digital counts.
Figure 33. Mean $\Delta E_{00}$ and RMS error (%) between measured and estimated reflectance in function of the number of non-zero adjacent to the diagonal from 0 to 5 using averaged digital counts.

Figure 34. Visualization of the transformation matrix from averaged digital signals to reflectance using NNLS transformation matrix with three non-zero adjacent lines around.

Table A.III.1 in the Appendix shows the dependency of spectral estimation accuracy of ColorChecker DC reflectances from camera signals on the order of the DST, in terms of the average values of the metrics. Table A.III.2 in the Appendix shows the dependency of spectral estimation accuracy of ColorChecker DC reflectances from camera signals on the order of the DST, in terms of the worst performance of the metrics. Table A.III.3 in the Appendix shows the dependency of spectral estimation accuracy of ColorChecker DC reflectances from camera signals on the order of the DST, in terms of the standard deviation of the values of the metrics.

Figure 38 shows the average $\Delta E^{*\text{ab}}_{00}$ and RMS error (%) plot between measured and estimated reflectance of ColorChecker DC varying the order of the DST from 3 to 31. Figure 39 shows the same information when the order of the DST from 3 to 31 in order to close up the region in which the colorimetric and spectral metric stabilizes.

Observing Tables A.III.1, A.III.2 and A.III.3 as well as Figures 35 and 36 it is possible to see that increasing the order from 3 to 31 improves the spectral estimation performance in terms of all considered metrics. However, the improvement stabilizes very quickly and the benefit of increasing the order of DST is negligible beyond ten. From Table A.III.1 it is possible to see that all average metric values reach an asymptote without reaching a perfect match showing the theoretical limit probably due to noise. We also observed the same trend for accuracy varying the order of the DST for the independent targets.

Since DST transformation is only the non-linear part of the MDST transformation its visualization is omitted since it does not have the meaning of the previous transformations.
Figure 35. Mean $\Delta E^{*}\text{00}$ and RMS error (%) between measured and estimated reflectance in function of the order of the DST transformation from 3 to 31 using averaged digital counts.

Figure 36. Mean $\Delta E^{*}\text{00}$ and RMS error (%) between measured and estimated reflectance in function of the order of DST from 3 to 12 using averaged digital counts.
Table III, IV, V and VI summarize the performance of the selected transformations for respectively pseudo-inverse, six eigenvectors, MDST with order 10 DST and NNLS with 3 non-zero adjacent lines to the diagonal.

**Table III.** Performance of the transformation from ColorChecker DC averaged narrow-band digital signals to reflectance using pseudo-inverse applied to all targets.

<table>
<thead>
<tr>
<th></th>
<th>(\Delta E_{ab}^*) (D50, 2°)</th>
<th>(\Delta E_{00}^*) (D50, 2°)</th>
<th>RMS (%)</th>
<th>(w\text{RMS} \text{ inverse} \ R(\lambda)) (%)</th>
<th>(w\text{RMS} \text{ diagonal}[R]) (%)</th>
<th>GFC (%)</th>
<th>Metamerism Index (D50, A, 1931, (\Delta E_{ab}^*))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ColorChecker DC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>1.3</td>
<td>0.9</td>
<td>0.7</td>
<td>1.9</td>
<td>0.2</td>
<td>99.79</td>
<td>0.1</td>
</tr>
<tr>
<td>Max/Min(GFC)</td>
<td>8</td>
<td>4</td>
<td>2.8</td>
<td>14.3</td>
<td>0.8</td>
<td>78.47</td>
<td>0.7</td>
</tr>
<tr>
<td>Standard Deviation</td>
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<td>0.7</td>
<td>0.3</td>
<td>1.6</td>
<td>0.1</td>
<td>1.42</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Paint chips</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>5.3</td>
<td>2.5</td>
<td>2.7</td>
<td>6.9</td>
<td>0.7</td>
<td>99.75</td>
<td>0.2</td>
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<tr>
<td>Max/Min(GFC)</td>
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<td>10.5</td>
<td>9.9</td>
<td>41.6</td>
<td>2.1</td>
<td>97.95</td>
<td>0.8</td>
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<tr>
<td>Standard Deviation</td>
<td>4.6</td>
<td>1.8</td>
<td>1.8</td>
<td>6.4</td>
<td>0.4</td>
<td>0.39</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Gamblin paints</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>4.5</td>
<td>3.2</td>
<td>4.5</td>
<td>9.3</td>
<td>1</td>
<td>99.33</td>
<td>0.7</td>
</tr>
<tr>
<td>Max/Min(GFC)</td>
<td>13.5</td>
<td>6.5</td>
<td>9.8</td>
<td>15.6</td>
<td>2.3</td>
<td>96.10</td>
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<td>Standard Deviation</td>
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<td>3.1</td>
<td>0.6</td>
<td>0.71</td>
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<td>Mean</td>
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<td>97.18</td>
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<td>7.8</td>
<td>0.4</td>
<td>0.66</td>
<td>0.6</td>
</tr>
</tbody>
</table>

**Table IV.** Performance of the transformation from ColorChecker DC averaged narrow-band digital signals to reflectance using six eigenvectors and least squares applied to all targets.

<table>
<thead>
<tr>
<th></th>
<th>(\Delta E_{ab}^*) (D50, 2°)</th>
<th>(\Delta E_{00}^*) (D50, 2°)</th>
<th>RMS (%)</th>
<th>(w\text{RMS} \text{ inverse} \ R(\lambda)) (%)</th>
<th>(w\text{RMS} \text{ diagonal}[R]) (%)</th>
<th>GFC (%)</th>
<th>Metamerism Index (D50, A, 1931, (\Delta E_{ab}^*))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ColorChecker DC</strong></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Mean</td>
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<td>1.3</td>
<td>3.3</td>
<td>0.0</td>
<td>99.674</td>
<td>0.2</td>
</tr>
<tr>
<td>Max/Min(GFC)</td>
<td>7.9</td>
<td>4.2</td>
<td>4.6</td>
<td>18.6</td>
<td>0.1</td>
<td>99.999</td>
<td>1.4</td>
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<tr>
<td>Standard Deviation</td>
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<td>0.8</td>
<td>0.7</td>
<td>2.4</td>
<td>0.0</td>
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<td></td>
</tr>
<tr>
<td>Mean</td>
<td>4.7</td>
<td>3.3</td>
<td>4.3</td>
<td>8.8</td>
<td>0.1</td>
<td>99.373</td>
<td>0.7</td>
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<tr>
<td>Max/Min(GFC)</td>
<td>13.9</td>
<td>6.9</td>
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<td>13.7</td>
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<td>99.858</td>
<td>1.6</td>
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<tr>
<td>Mean</td>
<td>5.5</td>
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Table V. Performance of the transformation from ColorChecker DC averaged narrow-band digital signals to reflectance using MDST applied to all targets.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta E_{ab}^{*}$ (D50, 2°)</th>
<th>$\Delta E_{00}^{*}$ (D50, 2°)</th>
<th>RMS (%)</th>
<th>$\text{wRMS}_{\text{inverse R(\lambda)}}$ (%)</th>
<th>$\text{wRMS}_{\text{diagonal}}$ ([R]) (%)</th>
<th>GFC (%)</th>
<th>Metamerism Index (D50, A, 1931, $\Delta E_{00}^{*}$)</th>
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<td>Mean</td>
<td>5.9</td>
<td>3.3</td>
<td>3.3</td>
<td>8.8</td>
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<td>99.303</td>
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</tr>
<tr>
<td>Mean</td>
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<td>99.309</td>
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<tr>
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<tr>
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<td>0.4</td>
<td>0.620</td>
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</table>

Table VI. Performance of the transformation from ColorChecker DC averaged narrow-band digital signals to reflectance using NNLS applied to all targets.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta E_{ab}^{*}$ (D50, 2°)</th>
<th>$\Delta E_{00}^{*}$ (D50, 2°)</th>
<th>RMS (%)</th>
<th>$\text{wRMS}_{\text{inverse R(\lambda)}}$ (%)</th>
<th>$\text{wRMS}_{\text{diagonal}}$ ([R]) (%)</th>
<th>GFC (%)</th>
<th>Metamerism Index (D50, A, 1931, $\Delta E_{00}^{*}$)</th>
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</thead>
<tbody>
<tr>
<td><strong>ColorChecker DC</strong></td>
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<tr>
<td>Mean</td>
<td>5.2</td>
<td>3.0</td>
<td>2.1</td>
<td>6.3</td>
<td>0.7</td>
<td>99.635</td>
<td>0.4</td>
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<tr>
<td>Max/Min(GFC)</td>
<td>25.2</td>
<td>12.5</td>
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<td>0.7</td>
<td>5.6</td>
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<tr>
<td>Mean</td>
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<td>4.3</td>
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<td>97.985</td>
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</tbody>
</table>
From Tables III to VI we can see that none of the methods was able to produce a reasonable result using average values of digital signals. Looking at Table III, IV and V, the mean values for the spectral estimation of the training target are very reasonable but the transformations did not result in very accurate spectra for the verification targets. Although NNLS is supposed to give a transformation that is reasonable in terms of physical correlation, its transformation resulted in poor accuracy for all targets.

III.1.B. Wide-band imaging using averaged digital signals

Table VII and VIII summarize respectively the results for the pseudo-inverse and eigenvector transformations built using the average digital signals of the GretagMacbeth ColorChecker DC.

**Table VII.** Performance of the transformation from ColorChecker DC averaged wide-band digital signals (using 6 glass filters) to reflectance using pseudo-inverse applied to all targets.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta E^{*\text{ab}}$ (D50, 2°)</th>
<th>$\Delta E^*_{00}$ (D50, 2°)</th>
<th>RMS (%)</th>
<th>$\text{wRMS inverse } R(\lambda)$ (%)</th>
<th>$\text{wRMS diagonal}(\text{[R]})$ (%)</th>
<th>GFC (%)</th>
<th>Metamerism Index (D50, A, 1931, $\Delta E^*_{\text{ab}}$)</th>
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<td>Mean</td>
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<td>1.3</td>
<td>1.8</td>
<td>4.8</td>
<td>0.4</td>
<td>99.5</td>
<td>0.6</td>
</tr>
<tr>
<td>Max/Min(GFC)</td>
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<td>4.4</td>
<td>30.8</td>
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<td>3.1</td>
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<td>1.2</td>
<td>0.6</td>
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<td>0.2</td>
<td>0.9</td>
<td>0.7</td>
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<tr>
<td>Mean</td>
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<td>2.5</td>
<td>3.0</td>
<td>7.1</td>
<td>0.9</td>
<td>99.6</td>
<td>0.7</td>
</tr>
<tr>
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<td>5.7</td>
<td>4.3</td>
<td>15.3</td>
<td>1.5</td>
<td>97.3</td>
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<td>1.6</td>
<td>0.6</td>
<td>3.2</td>
<td>0.2</td>
<td>0.6</td>
<td>0.7</td>
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<tr>
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<tr>
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<td>1.4</td>
<td>3.3</td>
<td>7.6</td>
<td>0.9</td>
<td>99.4</td>
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<td>2.9</td>
<td>0.2</td>
<td>0.9</td>
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</table>

**Table VIII.** Performance of the transformation from ColorChecker DC averaged wide-band digital signals (using 6 glass filters) to reflectance using six eigenvectors and least squares applied to all targets.
From Tables VII and VIII, it is possible to see that wide-band imaging in general produced better results than narrow-band. It indicates that none of the methods using averaged-based approach was able to generate a reasonable and stable transformation for narrow-band images. Moreover, for the wide-band images, the transformation using 6 eigenvectors outperformed the transformation using pseudo-inverse, probably because a 6 by 31 transformation is less stable than a least-square transformation after reducing the dimensionality with the aid of eigenvectors.

### III.2. Pixel-based approach

We used the GretagMacbeth ColorChecker DC to build the transformation matrix from a cluster of digital signals for each patch of the target and its corresponding spectral reflectances. We considered three imaging, one narrow-band approach using 31 LCTF bands and two wide-band approaches considering six glass filters and a combination of two RGB sets without and with absorption filter. We masked the patches of the targets to have a cluster of digital signals for each patch and used all the points to generate the 31 by 31 transformation for the narrow-band images and 31 by 6 transformations for the wide-band images. For example, for the LCTF images we used 1,155 digital signals for each patch of the ColorChecker DC; 4,489 digital signals for each patch of the Gamblin painting target; 21,209 digital signals for each patch of the color card painting chip target; and 10,403 digital signals for each patch of the ColorChecker rendition chart. The number of digital signals depends on the size of the square region masked in the images. The transformations were used to estimate the spectral reflectance of the corresponding masked images of the GretagMacbeth ColorChecker DC, and the independent data of

<table>
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<tr>
<th></th>
<th>∆E*ab (D50, 2°)</th>
<th>∆E*ab (D50, 10°)</th>
<th>RMS (%)</th>
<th>wRMS inverse R(λ) (%)</th>
<th>wRMS diagonal[R] (%)</th>
<th>GFC (%)</th>
<th>Metamerism Index (D50, A, 1931, ∆E*ab)</th>
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<td>Mean</td>
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<td>2.4</td>
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<td>99.6</td>
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<td>97.8</td>
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<td>1.7</td>
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<td>3.2</td>
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<td>1.5</td>
<td>3.5</td>
<td>8.2</td>
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<td>2.2</td>
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</table>
Gamblin paint target, GretagMacbeth ColorChecker and the paint chips. The metrics for spectral and colorimetric match quality were calculated for each estimated reflectance and the metrics statistics were averaged for each patch. Alternatively, we also could average the spectral reflectances for each patch before calculating the metrics, that would not produce very different results from the evaluation method we used (mentioned above). The statistics of the metrics are shown in Tables IX to XIII. These tables correspond to the following evaluations:

1. Table IX. LCTF imaging – pseudo-inverse method.
2. Table X. Six filters broad-band – pseudo-inverse method.
3. Table XI. Filtered and unfiltered RGB broad-band – pseudo-inverse method.
4. Table XII. Six filters broad-band – eigenvector method.
5. Table XIII. Filtered and unfiltered RGB broad-band – eigenvector method.

In these tables, we indicate the weighted RMS error for two illuminants: D65 and A standard illuminants. The metamerism index was also calculated in two ways. In the first metamerism index calculation we first matched the tristimulus values of the estimated curve to the measured spectra under D65 illuminant and then calculated the color difference ΔE*00 for A illuminant. In the second case, we matched the tristimulus values of the estimated curve to the measured spectra under A illuminant and then calculated the color difference ΔE*00 for D65 illuminant. Two degree observer was used for all colorimetric calculations.

**Table IX.** Performance of the pixel-based approach transformation from a cluster of ColorChecker DC LCTF narrow-band digital signals to reflectance applied to all targets using pseudo-inverse method.

<table>
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<th></th>
<th>ΔE*ab (D65, 2°)</th>
<th>ΔE*00 (D65, 2°)</th>
<th>RMS (%)</th>
<th>wRMS inverse R(λ) (%)</th>
<th>wRMS diagonal ([R], D65, 2) (%)</th>
<th>wRMS diagonal ([R], A, 2) (%)</th>
<th>GFC (%)</th>
<th>Metamerism Index (D65, A, 2°, ΔE*00)</th>
<th>Metamerism Index (A, D65, 2°, ΔE*00)</th>
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<td><strong>Paint chips</strong></td>
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</tr>
<tr>
<td>Max/Min(GFC)</td>
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</table>

Table X. Performance of the pixel-based approach transformation from a cluster of ColorChecker DC broad-band digital signals (6 glass filters) to reflectance applied to all targets using pseudo-inverse method.

<table>
<thead>
<tr>
<th></th>
<th>$\Delta E_{ab}^*$ (D$65$, 2°)</th>
<th>$\Delta E_{00}^*$ (D$65$, 2°)</th>
<th>RMS (%)</th>
<th>wRMS inverse R(Å) (%)</th>
<th>wRMS diagonal [R], D$65$, 2° (%)</th>
<th>wRMS diagonal [R], A, 2° (%)</th>
<th>GFC (%)</th>
<th>Metamerism Index (D$65$, A, 2°, $\Delta E_{00}^*$)</th>
<th>Metamerism Index (A, D$65$, 2°, $\Delta E_{ab}^*$)</th>
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<tr>
<td>Mean</td>
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<td>10.8</td>
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<td>2.0</td>
<td>5.3</td>
<td>0.5</td>
<td>99.58</td>
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<td>0.9</td>
</tr>
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<td>2.0</td>
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<td>0.5</td>
<td>99.76</td>
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<td>8.1</td>
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<td><strong>Gamblin paints</strong></td>
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<td>3.8</td>
<td>12.6</td>
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<td>1.2</td>
<td>96.69</td>
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Table XI. Performance of the pixel-based approach transformation from a cluster of ColorChecker DC broad-band digital signals (2 sets of filtered and unfiltered RGB) to reflectance applied to all targets using pseudo-inverse method.
<table>
<thead>
<tr>
<th></th>
<th>$\Delta E_{ab}^*$</th>
<th>$\Delta E_{ab}^*$</th>
<th>RMS (%)</th>
<th>$wRMS_{\text{inverse}}$</th>
<th>$wRMS_{\text{diagonal}}$</th>
<th>$wRMS_{\text{diagonal}}$</th>
<th>GFC (%)</th>
<th>Metamerism Index (D65, A, $2^<em>$, $\Delta E_{ab}^</em>$)</th>
<th>Metamerism Index (A, D65, $2^<em>$, $\Delta E_{ab}^</em>$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ColorChecker DC</strong></td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>2.9</td>
<td>2.1</td>
<td>2.3</td>
<td>5.4</td>
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<td>0.6</td>
<td>99.38</td>
<td>0.9</td>
<td>1.2</td>
</tr>
<tr>
<td>Max/Min(GFC)</td>
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<td>7.8</td>
<td>7.4</td>
<td>27.2</td>
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<td>1.4</td>
<td>90.31</td>
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<td>1.16</td>
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<td>Max/Min(GFC)</td>
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<td>6.3</td>
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<td>97.97</td>
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<td>4.3</td>
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<td>4.2</td>
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<td>90.40</td>
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<td>0.3</td>
<td>1.28</td>
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</table>

**Table XII.** Performance of the pixel-based approach transformation from a cluster of ColorChecker DC broad-band digital signals (6 glass filters) to reflectance applied to all targets using eigenvector method.
Table XIII. Performance of the pixel-based approach transformation from a cluster of ColorChecker DC broad-band digital signals (2 sets of filtered and unfiltered RGB) to reflectance applied to all targets using eigenvectors method.

<table>
<thead>
<tr>
<th>Metric</th>
<th>( \Delta E_{ab}^{*} ) (D65, 2(^\circ))</th>
<th>( \Delta E_{ab}^{*} ) (D65, 2(^\circ))</th>
<th>RMS (%)</th>
<th>wRMS inverse R((\lambda)) (%)</th>
<th>wRMS diagonal ([R], D65, 2(^\circ)) (%)</th>
<th>wRMS diagonal ([R], A, 2(^\circ)) (%)</th>
<th>GFC (%)</th>
<th>Metamerism Index (D65, A, 2(^\circ), ( \Delta E_{ab}^{*} ))</th>
<th>Metamerism Index (D65, A, 2(^\circ), ( \Delta E_{ab}^{*} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>ColorChecker DC</td>
<td></td>
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</tr>
<tr>
<td>Mean</td>
<td>2.9</td>
<td>2.1</td>
<td>2.4</td>
<td>5.6</td>
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<td>99.36</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Max/Min(GFC)</td>
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<td>7.9</td>
<td>7.4</td>
<td>29.0</td>
<td>1.6</td>
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<td>1.2</td>
<td>1.1</td>
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<td>0.6</td>
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<tr>
<td>Paint chips</td>
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<tr>
<td>Mean</td>
<td>3.1</td>
<td>2.4</td>
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<td>5.8</td>
<td>0.7</td>
<td>0.7</td>
<td>99.70</td>
<td>1.1</td>
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<tr>
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<td>6.8</td>
<td>4.0</td>
<td>12.6</td>
<td>1.3</td>
<td>1.2</td>
<td>98.39</td>
<td>3.7</td>
<td>4.5</td>
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<tr>
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<tr>
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<td>4.3</td>
<td>8.8</td>
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<td>98.95</td>
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<td>15.3</td>
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<td>2.4</td>
<td>90.36</td>
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<tr>
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<td>1.9</td>
<td>2.7</td>
<td>5.9</td>
<td>0.7</td>
<td>0.6</td>
<td>99.27</td>
<td>1.1</td>
<td>1.3</td>
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<tr>
<td>Max/Min(GFC)</td>
<td>8.4</td>
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<td>2.5</td>
<td>0.3</td>
<td>0.3</td>
<td>1.27</td>
<td>0.8</td>
<td>0.9</td>
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</table>

Tables XIV, XV, XVI and XVII summarize the performance of different imaging and spectral estimation methods for each target estimation, respectively, the ColorChecker DC, Gamblin paints, ColorChecker and color card paint chips. Three metrics are used; the \( \Delta E_{ab}^{*} \) calculated for D65 illuminant and 2 degree observer; the root mean square (RMS) error between measured and estimated reflectance; and the metamerism index where the estimated spectra is changed to match the measured spectra under D65 and 2 degree observer. Then, we calculated the \( \Delta E_{ab}^{*} \) under A and 2 degree observer between the measured and the modified spectra.

Two methods are shown in the tables: PCA (principal component analysis, i. e., eigenvector analysis) and PINV (pseudo-inverse transformation).

Table XIV. Spectral estimation evaluation result for the GretagMacbeth ColorChecker DC using pixel-based approach.

<table>
<thead>
<tr>
<th>Filtering method</th>
<th>31 Narrow-band channels by LCTF</th>
<th>6 Wide-band channels by designed Schott Glass filters</th>
<th>6 Wide-band channels RGB glass filters with and without Wratten</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transform</td>
<td>Metric</td>
<td>( \Delta E_{ab}^{*} ) (D65, 2(^\circ))</td>
<td>RMS (%)</td>
</tr>
<tr>
<td>Transform</td>
<td>Metric</td>
<td>( \Delta E_{ab}^{*} ) (D65, 2(^\circ))</td>
<td>RMS (%)</td>
</tr>
</tbody>
</table>
### Table XV. Spectral estimation evaluation result for the Gamblin paint target using pixel-based approach.

<table>
<thead>
<tr>
<th>Filtering method</th>
<th>Transform</th>
<th>Metric</th>
<th>ΔE*&lt;sub&gt;94&lt;/sub&gt; (D65, 2°)</th>
<th>RMS (%)</th>
<th>Metamerism Index (D65, A, 2°, ΔE*&lt;sub&gt;94&lt;/sub&gt;)</th>
<th>ΔE*&lt;sub&gt;94&lt;/sub&gt; (D65, 2°)</th>
<th>RMS (%)</th>
<th>Metamerism Index (D65, A, 2°, ΔE*&lt;sub&gt;94&lt;/sub&gt;)</th>
<th>ΔE*&lt;sub&gt;94&lt;/sub&gt; (D65, 2°)</th>
<th>RMS (%)</th>
<th>Metamerism Index (D65, A, 2°, ΔE*&lt;sub&gt;94&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCA</td>
<td>Average</td>
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<td>2.2</td>
<td>1.0</td>
<td>2.8</td>
<td>2.4</td>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max/Min(GFC)</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Std Dev</td>
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<td>1.3</td>
<td>1.1</td>
<td>1.2</td>
<td>1.4</td>
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<tr>
<td>PINV</td>
<td>Average</td>
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<td>2.1</td>
<td>0.9</td>
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</tr>
<tr>
<td>Max/Min(GFC)</td>
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<td>0.8</td>
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<td>0.7</td>
<td>1.2</td>
<td>1.0</td>
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</tr>
</tbody>
</table>

### Table XVI. Spectral estimation evaluation result for the ColorChecker using pixel-based approach.

<table>
<thead>
<tr>
<th>Filtering method</th>
<th>Transform</th>
<th>Metric</th>
<th>ΔE*&lt;sub&gt;94&lt;/sub&gt; (D65, 2°)</th>
<th>RMS (%)</th>
<th>Metamerism Index (D65, A, 2°, ΔE*&lt;sub&gt;94&lt;/sub&gt;)</th>
<th>ΔE*&lt;sub&gt;94&lt;/sub&gt; (D65, 2°)</th>
<th>RMS (%)</th>
<th>Metamerism Index (D65, A, 2°, ΔE*&lt;sub&gt;94&lt;/sub&gt;)</th>
<th>ΔE*&lt;sub&gt;94&lt;/sub&gt; (D65, 2°)</th>
<th>RMS (%)</th>
<th>Metamerism Index (D65, A, 2°, ΔE*&lt;sub&gt;94&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCA</td>
<td>Average</td>
<td></td>
<td>1.6</td>
<td>2.3</td>
<td>0.9</td>
<td>1.8</td>
<td>3.1</td>
<td>1.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max/Min(GFC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Std Dev</td>
<td></td>
<td></td>
<td>0.7</td>
<td>0.9</td>
<td>0.7</td>
<td>0.9</td>
<td>1.5</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PINV</td>
<td>Average</td>
<td></td>
<td>1.6</td>
<td>1.6</td>
<td>0.4</td>
<td>1.6</td>
<td>2.2</td>
<td>0.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max/Min(GFC)</td>
<td></td>
<td></td>
<td>8.1</td>
<td>6.8</td>
<td>4.2</td>
<td>3.5</td>
<td>4.5</td>
<td>2.7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Std Dev</td>
<td></td>
<td></td>
<td>1.6</td>
<td>1.2</td>
<td>0.8</td>
<td>0.6</td>
<td>0.9</td>
<td>0.6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table XVII. Spectral estimation evaluation result for the color card paint chips using pixel-based approach.

<table>
<thead>
<tr>
<th>Filtering method</th>
<th>Transform</th>
<th>Metric</th>
<th>ΔE*&lt;sub&gt;94&lt;/sub&gt; (D65, 2°)</th>
<th>RMS (%)</th>
<th>Metamerism Index (D65, A, 2°, ΔE*&lt;sub&gt;94&lt;/sub&gt;)</th>
<th>ΔE*&lt;sub&gt;94&lt;/sub&gt; (D65, 2°)</th>
<th>RMS (%)</th>
<th>Metamerism Index (D65, A, 2°, ΔE*&lt;sub&gt;94&lt;/sub&gt;)</th>
<th>ΔE*&lt;sub&gt;94&lt;/sub&gt; (D65, 2°)</th>
<th>RMS (%)</th>
<th>Metamerism Index (D65, A, 2°, ΔE*&lt;sub&gt;94&lt;/sub&gt;)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCA</td>
<td>Average</td>
<td></td>
<td>2.2</td>
<td>2.2</td>
<td>0.9</td>
<td>2.5</td>
<td>2.4</td>
<td>1.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
From Tables IX to XVII, it is possible to see that the narrow-band imaging pseudo-inverse transformation presented the best performance followed by the transformation given by the six wide-band glass filters and finally the six wide-band images using RGB with and without Wratten filter. The eigenvector transformation and the pseudo-inverse transformation for both wide-band imaging presented no significant difference in terms of performance indicating that six eigenvectors should be sufficient for the present estimation accuracy.

Figure 37 shows a visualization of the transformation matrix from digital signals to reflectance using pseudo-inverse transformation matrix for narrow-band images using a cluster of pixels (pixel-based approach). From the shape of figure 37, it is possible to observe that this transformation has the desirable shape with high correlation in the diagonal region and at the same time this transformation considers the influence of the noise in the variability of the digital signals.

Comparing all figures and tables in this section we can conclude that the method and approach that provides the best transformation is LCTF pseudo-inverse transformation generated using pixel-based approach.

<table>
<thead>
<tr>
<th>PINV</th>
<th>Max/Min(GFC)</th>
<th>Std Dev</th>
<th>Average</th>
<th>Std Dev</th>
<th>Max/Min(GFC)</th>
<th>Std Dev</th>
<th>Average</th>
<th>Std Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.4</td>
<td>0.7</td>
<td>2.1</td>
<td>1.0</td>
<td>4.7</td>
<td>1.0</td>
<td>2.4</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>6.3</td>
<td>1.6</td>
<td>1.9</td>
<td>1.0</td>
<td>5.0</td>
<td>1.0</td>
<td>2.4</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>3.8</td>
<td>0.9</td>
<td>0.7</td>
<td>0.5</td>
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<td>3.9</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
<td>0.8</td>
<td>2.2</td>
<td>0.7</td>
<td>4.4</td>
<td>0.7</td>
<td>6.8</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>6.8</td>
<td>1.7</td>
<td>2.2</td>
<td>1.6</td>
<td>6.3</td>
<td>1.6</td>
<td>3.7</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>3.7</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>3.9</td>
<td>0.9</td>
<td>2.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>

**Figure 37.** Visualization of the transformation matrix from digital signals to reflectance using pseudo-inverse transformation matrix for narrow-band images using a cluster of pixels (pixel-based approach).
Figure 38 and 39 shows the absolute spectral reflectance difference plot when we used pixel-based approach, pseudo-inverse method and narrow-band imaging with transformation built for the ColorChecker DC and applied to respectively the ColorChecker and the Gamblin Painting target. The reflectances were calculated for each pixel inside the masked region of each patch and later averaged within the patch.

Tables A.IV.1 and A.IV.2 in the Appendix show the colorimetric and spectral evaluation of the estimated spectral reflectance using the transformation derived from ColorChecker DC using the pixel-based approach, pseudo-inverse method, for respectively the Gamblin paints and the ColorChecker DC. Figures A.I.1 to A.I.6 of the Appendix show a comparison plot of the measured and estimated spectral reflectances of the ColorChecker using the transformation generated by the pixel-based approach, pseudo-inverse method, for respectively the Gamblin paints and the ColorChecker DC.

![Figure 38. Absolute spectral reflectance difference between measurement and estimation of the ColorChecker using pseudo-inverse transformation in pixel-based approach generated by the ColorChecker DC.](image)

**Figure 38.** Absolute spectral reflectance difference between measurement and estimation of the ColorChecker using pseudo-inverse transformation in pixel-based approach generated by the ColorChecker DC.
The big error in the Table XI corresponds to the black of the ColorChecker as shown in Table A.IV.2 and Figure A.I.f. Imaging artifact on the region of the black patch of the ColorChecker is responsible for this maximum colorimetric and spectral error. The same kind of imaging artifact in a form of a reflection was also present in the white patch explaining the reason for the spectral error shown in Figure A.I.5.

The comparison between measured and estimated spectral reflectances for each patch of the Gamblin target is shown in the Figures A.II.1 to A.II.60 in the Appendix, where the estimated reflectances were derived from a pixel-based pseudo-inverse transformation based on the ColorChecker DC for a narrow-band imaging using LCTF. It is possible to see that for the most of the cases, the estimated reflectance matched well the measured reflectance, even in color such as cobalt blue shown in Figures A.II.47 and A.II.55 that whose near infra-red tail cannot be reproduced accurately using broad-band approaches.50
IV. Discussions

It was observed that the LCTF pseudo-inverse transformation using all pixels produced the best results overall but the wide-band imaging using this approach also produced reasonable results. When the average digital signal values of the patches were used for pseudo-inverse method, it did not generate satisfactory results for the verification targets because the transformation does not show a strong correlation with the filter transmittances presenting strongly negative values in the matrix. One of the factors that could be influencing the results is imaging noise. We solved to use a cluster of digital signals for each patch instead of the average value, as mentioned above, in order to generate the pseudo-inverse transformation. This approach generated both physical and mathematical consistency since having a cluster of pixels took in account the noise and the pseudo-inverse produced a transformation with strong correlation between digital signals and reflectance.

The results in this report do not take in account image quality. In order to evaluate visually RGB images rendered from the estimated spectral images using different transformations from digital counts to reflectance, a psychophysical experiment is necessary. Currently, there is an experiment in progress to consider both color reproduction and image quality. In this experiment a computer display monitor is colorimetrically characterized to match the colors of objects inside a viewing booth beside the monitor. The transformation to calculate spectra from digital signals then is used to display the image on the monitor and compared to the original objects inside the booth. The comparison could be accomplished by both visual inspection of the targets and pictorial image as well as comparing the spectral radiance from the uniform regions of the objects.

We still have to accomplish improvements in our imaging system in order to reduce the influence of imaging artifacts such as flare and reflections that can change the results as we observed in our experiments.

We are also considering improvement of our transformation using a more sophisticated Wiener filtering or considering Kalman filtering.

References


52) N. Matsushiro, F. H. Imai and N. Ohta, Principal component analysis of spectral images based on the independence of color matching function vectors, in Proc. of Third International


S. Tominaga, Spectral imaging by a multichannel camera, J. Electronic Imaging 8, 332-341 (1999).


